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Membrane distillation: Perspectives for sustainable and improved desalination

Daniel González[a,b], José Amigo[a,b,c], Francisco Suárez[a,b,c,d,*]

[a] Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Avda. Vicuña Mackenna 4860, Macul, Santiago, Chile
[b] Center for Solar Energy Technologies (CSET), Santiago RM, Chile
[c] Centro de Desarrollo Urbano Sustentable (CEDEUS), CONICYT/FONDAP/15110020, Santiago RM, Chile
[d] Centro de Excelencia en Geotermia de los Andes (CEGA), Santiago RM, Chile

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ABSTRACT

Membrane distillation (MD) is a promising separation technology that can help reducing the worldwide water-energy stress in a sustainable way. MD uses low-grade thermal energy to drive desalination, to remove non-volatile contaminants or to recover other components. In MD, the vapor from an aqueous solution crosses a hydrophobic membrane and then it condensates at the other side of the membrane, resulting in a high-quality distillate. Recent advances in MD have demonstrated the viability of this technology for different water purification applications. This article presents a critical review of MD that focuses on applications for sustainable water production and on issues that must be addressed to improve the performance of MD desalination systems. To achieve sustainable desalination, different MD systems powered by solar, geothermal, and waste energy have been designed and evaluated, as well as hybrid systems that allow accomplishing zero liquid discharge. To achieve improved desalination, new membranes, membrane modules and MD configurations have been proposed in the last years. Membrane fouling and scaling has been found to be one of the main issues that limits MD at large-scale. Research gaps are highlighted and areas for further research – in terms of sustainability and to improve the performance of MD systems– are proposed.

1. Introduction

Water and energy are closely related and both are commodities that the world requires urgently –freshwater scarcity is a problem that is expected to increase in the future due to growth of population pressure, higher welfare, production of water intensive biofuels and climate change [1]. Many measures have been implemented to solve this problem, being one of them water reuse through desalination. However, large amounts of energy (~50–70 kW h/m^3 for thermal processes and 3–6 kW h/m^3 for electric energy demanding processes such as RO [2]) are needed for water desalination [3]. Fossil fuels are the common alternative for energy supply, but these fuels are not sustainable due to the environmental effects of combustion and the rapid depletion of fossil fuel reserves [4,5]. Therefore, sustainable energy and methods are needed for freshwater production.

Membrane distillation (MD) is a temperature-driven separation process that can help reducing the water-energy stress that our society is facing. MD is used for applications such as desalination, removal of small molecule contaminants, and recovery of other components [6]. In MD, the volatile components of a feed solution evaporate and cross a microporous hydrophobic membrane; then, these volatile components condensate in a distillate (permeate) solution. This process results in a highly pure distillate solution and a concentrated feed solution where the non-volatile solutes are retained [7]. The driving force of MD is the vapor pressure difference between the feed and distillate solutions, which causes evaporation at the feed side of the membrane and condensation at the distillate side. The

Abbreviations: MD, Membrane distillation; MED, Multi-effect distillation; ZLD, Zero liquid discharge; PTFE, Polytetrafluoroethylene; PVDF, Polyvinylidene fluoride; AGMD, Air gap membrane distillation; SGMD, Sweep gas membrane distillation; HFP, Hexafluoropropylene; PES, Polyethersulfone; PPESK, Polyphthalazinone ether sulfone ketone; FO, Forward osmosis; MGMD, Material-gap membrane distillation; MEMD, Multi-effect membrane distillation; OMD, Osmotic membrane distillation; MBR, Membrane bioreactors; NF, Nanofiltration; MDC, Membrane distillation crystallization; LCA, Life cycle assessment; LCIA, Life cycle impact assessment; RO, Reverse osmosis; MSF, Multistage flash; LEP, Liquid entry pressure; PP, Polypropylene; DCMD, Direct contact membrane distillation; VMD, Vacuum membrane distillation; GOR, Gain output ratio; TFE, Tetrafluoroethylene; PS, Polysulfone; CNT, Carbon nanotube; VEDCMD, Vacuum-enhanced direct contact membrane distillation; PGMD, Permeate-gap membrane distillation; V-MEMD, Vacuum-multi-effect membrane distillation; CFD, Computational fluid dynamics; MF, Microfiltration; MC, Membrane crystallization; MINLP, Mixed-integer nonlinear programming; LCI, Life cycle inventory

* Corresponding author at: Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Avda. Vicuña Mackenna 4860, Macul, Santiago, Chile.
E-mail address: fsuarez@ing.puc.cl (F. Suárez).

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Table 1
Comparison of different desalination technologies [6,9,10,15,209–212].

Desalination technology	Method	Driving force	Thermal energy consumption (kW h/m^3 of distillate water)	Electric energy consumption ((kW h/m^3 of distillate water)	Resulting water quality (ppm)	Use in the market – 10^6 m^3 of distillate per year	Advantages
Membrane Distillation (MD)	Membrane filtration and distillation	Vapor pressure (thermal)	120–1700	0.6–1.8	< 10	Emerging (< 2%) < 1.80	Operates with low-grade thermal energy and low pressures; less requirements on membrane mechanical properties; large contact area per unit of equipment volume
Reverse Osmosis (RO)	Membrane filtration	Hydraulic pressure	–	2.5–7.0	200–500	Most used (~65%) 58.57	Modular construction and small footprint
Multi-Effect Distillation (MED)	Distillation	Thermal	40.3–63.9	2.0–2.5	< 10	Very used in the past and is currently re-emerging (~7%) 6.31	More flexible to operate at partial loads than MSF, less sensitive to scaling, and more appropriate for limited capacity.
Multi-Stage Flash (MSF)	Distillation	Thermal	52.8–78.3	2.5–5.0	< 10	Second most used (~21%) 18.92	Suitable for the desalination of low- quality water (robust enough to tackle adverse conditions)
Forward Osmosis (FO)	Membrane filtration	Osmotic pressure	–	< 30	–	Emerging (< 2%) < 1.80	Low or no hydraulic pressure; lower and reversible membrane fouling; high salt rejection; negligibly affected by a variety of contaminants in the feed solution